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Anomalies in the gamma-ray diffuse emission of the Galaxy and implications for the interpretation of IceCube results

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Abstract. Several independent analyzes of Fermi-LAT results found evidences of an excess of γ-ray diffuse emission along the inner Galactic plane and of a related spatial dependence of the cosmic ray (CR) proton spectral index. These features are not accounted for by conventional models of CR transport. We show that a phenomenological model accounting for those results in terms of spatial dependent CR transport also reproduces the γ-ray excess found by Milagro at 15 TeV in the inner Galactic plane and by H.E.S.S. in the Galactic center. We then use that model to compute the neutrino emission along the Galactic plane finding that is significantly larger than expected on the basis of conventional models. This emission is compatible with ANTARES upper limits and may soon be detected by IceCube or, more likely, by Km3NeT.

1 Introduction

The γ-ray diffuse emission of the Galaxy is produced by the interaction of the cosmic ray (CR) sea with the interstellar medium (ISM) gas. This emission is modeled integrating along the line of sight the product of the (energy dependent) scattering cross-section, the gas density distribution and the CR spectral density. The latter quantity is probed only locally so that its large scale distribution has to be inferred solving the CR transport equation for a given source distribution using suitable analytical or numerical tools. Until recently this was done under the hypothesis that the propagation properties are the same in the whole Galaxy. This assumption, which is not supported by any compelling theoretical argument, has been recently questioned by several independent analysis of Fermi-LAT measurements which found evidences of a dependence of the CR proton spectral index on the Galactocentric radius [1–3]. It was shown that this behaviour is at the origin of the excess of γ-ray diffuse emission found by Fermi-LAT along the inner Galactic plane [4] growing with energy above few GeV.

A phenomenological model (KRA$_\gamma$) has been proposed in [1] which accounts for those findings in terms of a radial dependent diffusion coefficient. The model also assumes that the CR spectral hardening found by PAMELA [5] and AMS-02 [6] at ~ 250 GeV, as required to consistently match CREAM data [7], is a feature present in the whole Galaxy.

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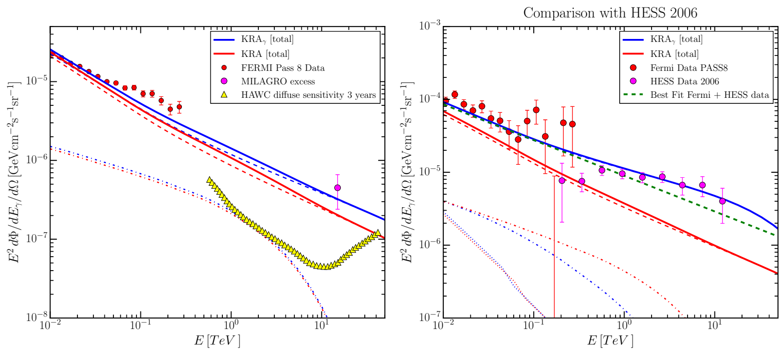

Figure 1. *Left panel*: The diffuse emission γ-ray spectrum measured by Fermi-LAT (PASS8) and Milagro in the inner Galactic plane ($|b| < 2°$, $30° < l < 65°$) is compared with the KRA (conventional) and KRA$_\gamma$ model predictions. The expected sensitivity of HAWC is reported. The main spectral components (π^0 decay: dashed; Inverse Compton: dot-dashed; bremsstrahlung: dotted) are also shown. *Right panel*: The same models are compared with H.E.S.S. and Fermi-LAT (PASS8) data for the diffuse emission in the Galactic ridge region: $|l| < 0.8°$, $|b| < 0.3°$. Point sources from the 3FGL Fermi catalogue are subtracted from those data. A single power-law fit of H.E.S.S. + Fermi-LAT data is also reported.

In Sec. 3 we will compare the KRA$_\gamma$ predictions with γ-ray data taken by Milagro [8] and H.E.S.S. [9] at energies above the TeV in the inner Galactic plane (GP) and Galactic center (GC) regions respectively. Since in the inner GP the γ-ray diffuse emission is mainly of hadronic origin, our results have direct implications for neutrino physics which will be discussed in Sec.4.

2 The model

The model proposed in [1] assumes that the exponent δ determining the rigidity dependence of the CR diffusion coefficient has the following Galactocentric radial dependence: $\delta(R) = AR + B$ where $A = 0.035$ kpc^{-1} and $B = 0.21$ so that $\delta(R_\odot) = 0.5$. The model also adopts a convective wind for $R < 6.5$ kpc with velocity $V_C(z)\hat{z}$ (z is the distance from the GP) vanishing at $z = 0$ and growing as $dV_c/dz = 100$ km s^{-1} kpc^{-1} as motivated by the X-ray ROSAT observations.

The observed γ-ray spectra at both low and mid Galactic latitudes, including the Galactic center, are reproduced by this model without spoiling local CR observables: proton, antiproton and Helium spectra, B/C and ^{10}Be/^{9}Be ratios. We implement the setup with `DRAGON`, a numerical code designed to compute the propagation of all CR species [10] in the general framework of position-dependent diffusion. We consider only proton and Helium CR nuclei since heavier species give a negligible contribution to the γ-ray emission. For their primary spectra here we assume a broken power law with index $\Gamma = 2.35/2.48$ below/above $\sim$ 250 GeV/n and an exponential cutoff at $E_{\rm cut} = 50$ PeV such to reproduce PAMELA, CREAM and KASCADE-Grande [11] data.

3 Comparison with γ-ray data

Milagro water Cherenkov observatory measured the γ-ray flux in the sky window with $|b| < 2°$ and $30° < l < 65°$ at a median energy of 15 TeV. This was found to be 4σ above the predictions of a conventional models tuned on CR data available in 2008 [8]. Almost forgotten until recently, *the Milagro anomaly* holds however also considering updated conventional models based on Femi data.

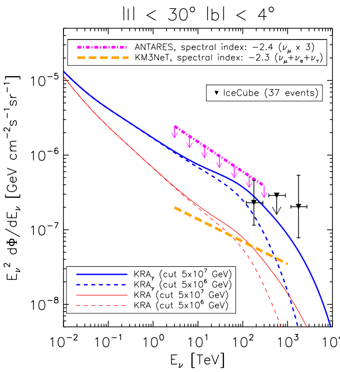

Figure 2. Total neutrino spectra in the inner Galactic plane computed for the conventional KRA and the novel KRA$_\gamma$ models for two different cutoff of CR primaries. We also show the maximal flux, estimated considering 3 years of IceCube HESE events, the constraint from ANTARES experiment as well as the deduced sensitivity of the future Mediterranean observatory KM3NeT after 4 years of lifetime.

This is visible in Fig. 1 (left panel) where a reference conventional (KRA) model tuned to reproduce local CR data as well as the large scale γ-ray diffuse emission measured by Fermi-LAT falls short of Milagro data point by several sigmas. The same discrepancy holds for other conventional models. Also the KRA model used here adopts the same CR hardening at $\sim$ 250 GeV/n as the KRA$_\gamma$ one. It is evident from Fig.1 that the presence of that feature in the whole Galaxy is not sufficient to explain *the Milagro anomaly*. From the same figure the reader can see as the KRA$_\gamma$ model is more successful as it matches the Milagro point and it is in better agreement with PASS8 Fermi-LAT data at lower energies.

We now check the KRA$_\gamma$ model against H.E.S.S. and Fermi-LAT data in the Galactic ridge region: $|l| < 0.8°$, $|b| < 0.3°$. We show here, for the first time, as the PASS8 reconstruction algorithm allows to bridge Fermi-LAT data with H.E.S.S. so to cover the 10 GeV – 10 TeV energy interval. The combined spectrum can be fit with a single power-law with index 2.49 ± 0.3. Again, this is significantly harder than expected for conventional models (see red line in Fig. 1, right panel).

Rather, we see from the same figure as the KRA$_\gamma$ model, predicting a harder CR spectrum in the GC, is in good agreement with the data. Noticeably, not only the slope but also the spectrum normalization are correctly reproduced by this model. This finding can hardly be interpreted as a coincidence and provides a further evidence in favor of the scenario proposed in [1]. We notice that respect to that work we used here the more detailed gas density distribution model in the central molecular zone described in [12].

4 Implications for Neutrino Astronomy

The hadronic component of the diffuse γ-ray emission discussed in the previous section is accompanied by a neutrino emission of similar intensity. We computed its spectrum as described in [13, 14] accounting for neutrino oscillations the effect of which is to redistribute the flux among the three flavors almost equally.

Here we consider the sky window $|l| < 30°$ and $|b| < 4°$ where the Galactic neutrino emission is expected to be dominant. For this region the ANTARES collaboration provided an upper limit on the muon neutrino flux based on the result of an unblinding analysis regarding the events collected between 2007 and 2013 in the energy range [3 ÷ 300] TeV [15].

In Fig. 2 we compare the ν_μ flux computed with the KRA (conventional model) and KRA$_\gamma$ setups with that experimental constraint. We notice the large enhancement (almost a factor of 5 at 100 TeV) obtained with the KRA$_\gamma$ model respect to the conventional scenario. Indeed, while – in agreement with previous results – we find that the flux corresponding to the KRA model may require long time of observation even by the KM3NeT observatory, our prediction for the KRA$_\gamma$ model is instead well above the sensitivity reachable by that experiment in 4 years and it is almost within the ANTARES observation capabilities. Interestingly, our result is in good agreement with the maximal flux which we inferred from the fraction of IceCube HESE events compatible with that region. A good agreement with IceCube results was also found on the whole Galactic plane (see e.g. Fig. 1 in [16]).

On the whole sky, the diffuse Galactic emission computed with the KRA$_\gamma$ model can account up to $\sim$ 15% (to be compared to $\sim$ 8% obtained for the conventional set-up [17]) of the flux measured by IceCube. Clearly an extra-Galactic (EG) contribution must be invoked to account for all IceCube event as well as for their almost isotropic distribution.

5 Conclusions

We showed that a Galactic CR model adopting a proper radial dependence for the diffusion coefficient so to reproduce Fermi-LAT results [1], also matches Milagro in the inner Galactic plane and H.E.S.S. measurements in the Galactic ridge. We showed that the Galactic neutrino emission computed in the same model is significantly larger than the predictions of conventional CR propagation models. Our results are in agreement with ANTARES and IceCube upper limits and will be testable by Km3NeT.

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